Steady-State and Dynamic Study of Photovoltaic (PV) System in University of New Haven: Towards to a Green and Secure Campus

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Abstract

In this study, several kinds of PV modeling methods have been discussed in order to find a best way to simulate solar power generation system in University of New Haven. To help the PV system produce maximum power output in certain conditions, a maximum power point tracking (MPPT) technique is employed. The PV solar systems vary from configurations due to the way the power injected into the grid may be different. There are lots of algorithms of the MPPT can be deployed to satisfy different actual needs to get the maximum power output. A 60 KW PV system is being constructed in University of New Haven and will come into service in 2015. The system will display real-time power generation and energy savings though a website and building monitor. The peak power of the PV system is enough to power up to 12 houses. The power generated can also be used as a backup of the fire alarm system. The PV systems will reduce the electricity bill of the university and help build up an environmental friendly green campus. On the other hand, the penetration of solar power may bring about challenges to existing power systems, such as voltage fluctuation and harmonics. Therefore, it is essential to model the PV system and simulate its impacts on the electric system of the university.

1. Introduction

Photovoltaic (PV) generators use photovoltaic technology to generate clean and sustainable energy and have a prosperous development foreground. Nowadays, researches of PV technology are working on the reduction of power losses and the utilization of solar irradiance which happens inscrutable due to solar activity [1]. A good PV system should be operated with high efficiency and stable output under certain environmental conditions. Environmental conditions are vital to a PV system due to the power generating process mainly depends on solar energy [2]. A PV unit could provide power to loads without exchanging power through power grids [3]. While the power may be unstable because of fluctuation of solar irradiance, the impact on the output of PV system can be enlarged if the semiconductor cannot satisfy the environmental needs, like average temperature and average duration of sunshine. Power quality is what matters to the PV system itself and the power systems. The major impacts may be posed to the system include the overloading of the feeders, low efficiency, low reliability and high maintenance cost [4].

Photovoltaic effect is a basic physical process through which solar energy is directly converted into electrical energy. The physics of a PV cell, or solar cell, is similar to the classical p-n junction diode, as shown in Fig.7. At night, a PV cell can be considered as a diode that consumes power. When the cell is illuminated, the energy of photons is transferred to the semiconductor material, resulting in the creation of electron-hole pairs. The electric field created by the p-n junction causes the photon-generated electron-hole pairs to separate. The electrons are accelerated to n-region (N-type material), and the holes are dragged into p-region (P-type material). The electrons from n-region flow through the external circuit and provide the electrical power to the load at the same time.

2. Load Profile in UNH

The power consumption in University of New Haven are as shown in Figs. 1-3.

Fig.1. Loads in University of New Haven

Fig.2. Power consumption from Mar 2012 to Jan 2015

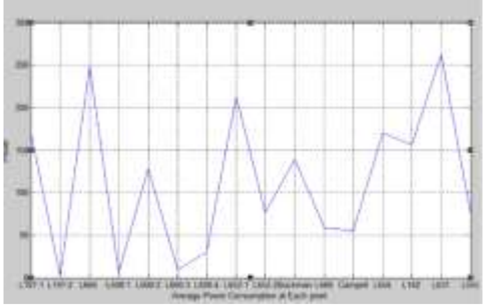

Fig.3. Average power consumption in each point

3. Types of PV Array/System

A common method is to connect the collector panel with the power grid through a fully controlled inverter, as shown in Fig. 4. Fig. 5 shows the second way which splits the power by using a hybrid (DC/AC) inverter to support both of the DC and AC loads. In the third method shown in Fig. 6, the PV system is employed to charge/discharge a battery bank with the MPPT algorithm, and the battery is controlled to supply energy to the grid.

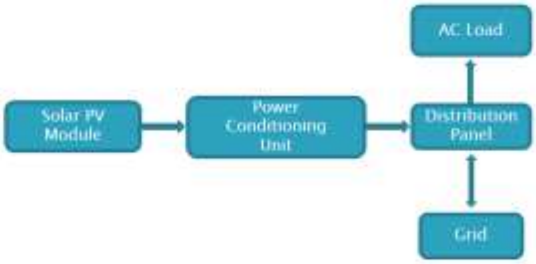

Fig.4. Block Diagram of Grid-connected Solar PV System

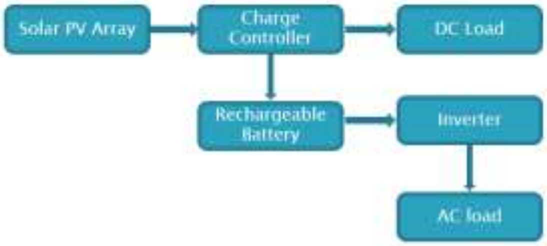

Fig.5. Block Diagram of Stand-alone PV System with Battery Storage

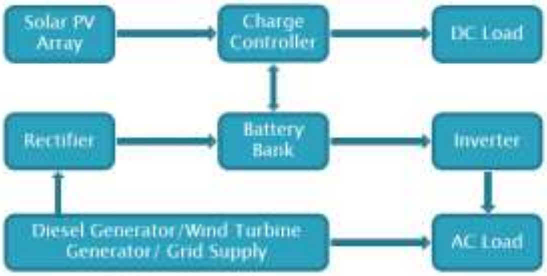

Fig.6. Block Diagram of Photovoltaic Hybrid System

4. Basics of PV Generation

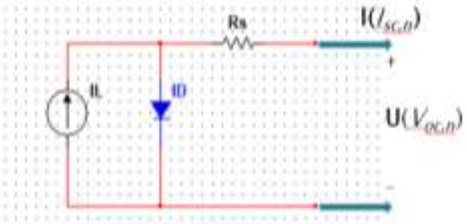

Fig.7. One diode equivalent model of a PV cell

The basic equations that describe the current-voltage (I-V) characteristics of ideal PV cells are

$$\boldsymbol{I_{PV} = I_{PV,cell} - I_{O,cell}\left[\exp\left(\frac{qV}{\alpha kT}\right) - 1\right]} \quad (1.1)$$

$$\boldsymbol{I = I_{PV} - I_0\left[\exp\left(\frac{V+R_S I}{(V_t\alpha-1)}\right)\right] - \frac{V+R_S I}{R_P}} \quad (1.2)$$

where α is the thermal voltage timing completion factor.

The main idea of current-based MPPT is that the current at the maximum power point I_{MP} has a linear relationship with the short circuit current I_{SC} as shown in Fig. 8. The relationship can be expressed as

$$\boldsymbol{I_{MP} = K_{CMPPT} * I_{SC}} \quad (1.3)$$

where K_{CMPPT} is the current factor CMPPT control, and I_{SC} can be measured or calculated from a valid model [8].

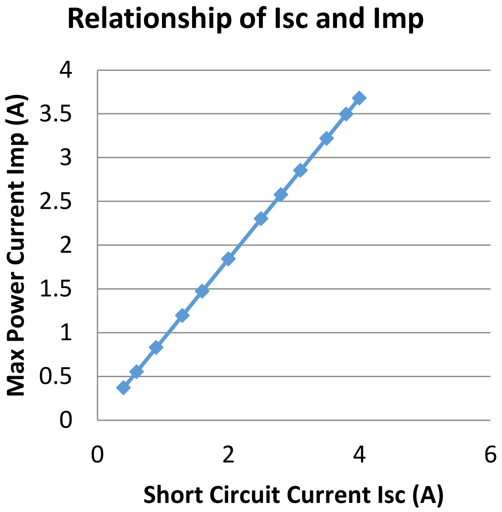

Fig.8. Relationship of I_{SC} and I_{MP}

5. Introduction of MPPT

The purpose of the MPPT technique is to maximize the power generation of the PV system. When the PV system is connected to a power converter, maximizing the PV array power also maximizes the output power of the load of the converter [9]. In this situation, the converter is assumed to be lossless. Most loads can be simplified as a combination of a set of voltage source, current source and resistance or one of them. For different types of load, a different item of the PV system should be maximized in order to obtain the maximum output. For instance, the load current should be maximized if the load is modelled as a voltage source. For loads of the types of current source and resistance, both output current and output voltage can be maximized to get a maximum power. This is true for any load types only if they show no negative impedance characteristics [9]. Normally, it is adequate to maximize load voltage or load current in order to get the maximum power output. For most PV systems, the battery is viewed as constant voltage source load and plays a role of energy storage to guarantee the energy security in emergent conditions.

Different MPPT techniques are listed and compared in Fig. 9.

MPPT Techniques	Analog or Digital	Convergence Speed	Complexity	Sensed Parameter
Hill-climbing	Both	Varies	Low	V & I
Neural Network	Digital	Fast	High	Varies
Current Sweep	Digital	Slow	High	V & I
Linear current control	Digital	Fast	Medium	Irradiance
MPP I&V computation	Digital	N/A	Medium	Irradiance & Temp
State-based MPPT	Both	Fast	High	V & I

Fig.9. Comparison of MPPT techniques

1). Hill-climbing technique

The hill-climbing technique named as the shape of the power-voltage (PV) curve. This technique can be divided into three sub-techniques including Perturb and Observe algorithm (P&O), Modified Adaptive method and Incremental Conductance (INC) algorithm. The efficiency can be higher than 96%.

The advanced hill-climbing method consists of different techniques along with the hill climbing method for fast and accurate tracking of the maximum power. The voltage and current controlled algorithms are more accurate and effective at low solar radiation conditions. Therefore these methods are combined with P&O or INC algorithms to increase their effectiveness. The hill climbing based algorithms oscillate around the MPP in slow varying atmospheric conditions. Therefore, the hill climbing based algorithms are only suitable in rapidly changing conditions, and the constant voltage method is fast and sufficient for constant conditions [5].

2). Neural Network Architecture

Recently, the ANN has been used for the MPPT because of its capability of good pattern recognition. A three-layer neural network can fairly simulate any nonlinear functions with a random accuracy. A three layer ANN including an input, a hidden layer and an output layer to guess the duty cycle of DC-DC boost converters. The input layer consists of a two dimensional vector: one is the DC output voltage of PV modules, and the other is the PV output current. The output layer is a one-dimensional vector consisting of duty cycles. The neural network modifies the weights and biases of the network to enhance network performance. The connection weights are modified until the best fit is attained for the input–output patterns based on minimum errors.

3). State-Flow MPPT

Stat-Flow is proposed as a competitive MPPT technique featuring simplified implementation, high degree-of-freedom, and controllable event timing. Those features are expected to enhance MPPT tracking by minimizing the steady-state power oscillations and improving the transient performance. This method repeats the perturbation process periodically, causing the system to oscillate around its maximum power point in steady state. However, the algorithm may move the operating point far from the point under rapidly changing atmospheric conditions [7].

6. Simulations in Matlab

Figs. 10-12 are Matlab models built in order to simulate the output of the PV system. Fig.10 is the equivalent model of a single PV cell. In this design, twelve of PV cells connected in series becomes a PV module and twelve of PV modules connected in series is a PV array. Each PV subsystem in Fig.12 is expected to generate 5 kW of power. Every subsystem is consist of 5 PV arrives whose power output is set to be 1kW.

The equations showed below in Fig.12 are equations transformed from mathematical equations to Matlab equations which is applied into the PV cell design. The overall design of the PV system is capable of generating 60 kW of power which consist of 12 of 5 kW PV subsystems connected together.

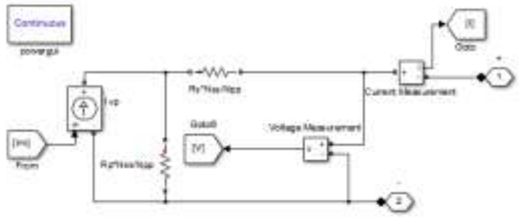

Fig.10. Equivalent Matlab/Simulink Model of a PV Module

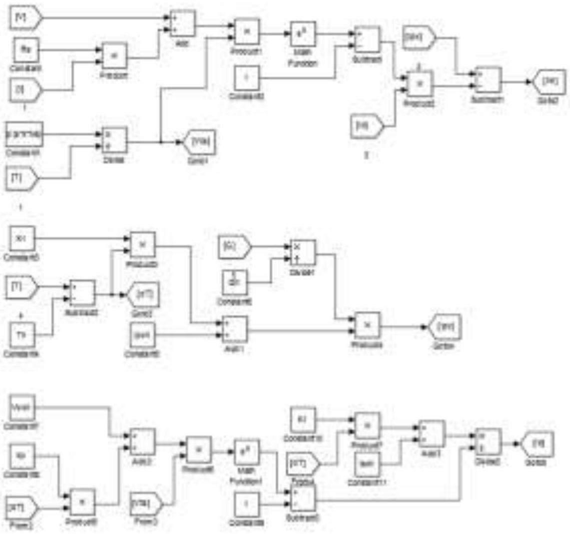

Fig.11. Equations in Simulink

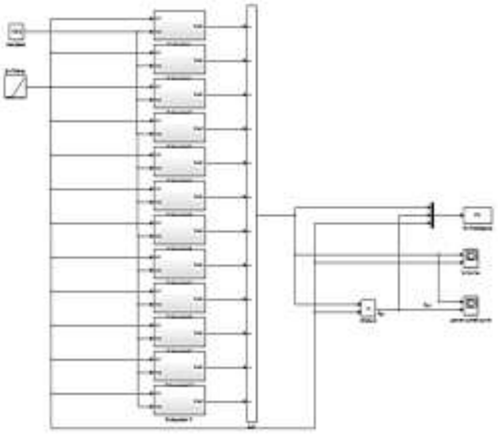

Fig.12. Overall model of a PV array

7. Results

Fig.13 – 16 are simulation results of the Matlab design of one single PV array. It is easy to indicate from Fig.14 that the maximum output power is approximately 1 kW at the output voltage of approximately 200v. At the same time, the output current at output voltage of 200v is around 5 amps.

Just as mentioned, the irradiation of the Sun has a great impact on the solar power generation and the efficiency. It is easy to notice that the drop of power output is significant and so does the output current.

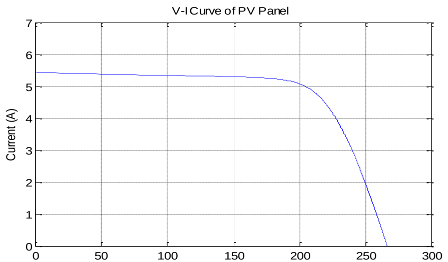

Fig.13. V-I curve of PV panel

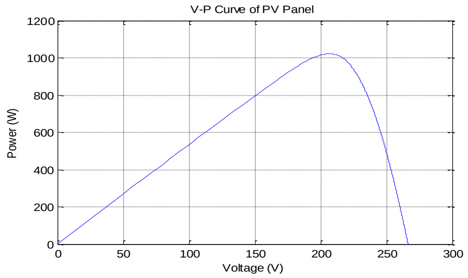

Fig.14. V-I curve of PV panel

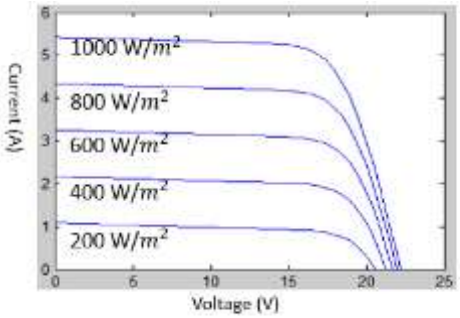

Fig.15. V-I Curve of the PV system Deployed Irradiation difference

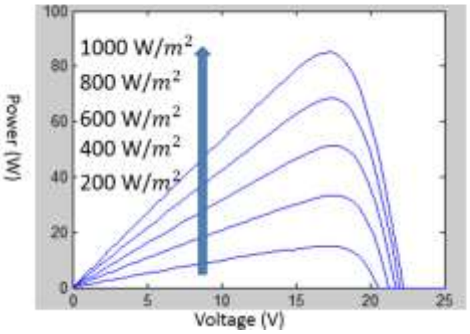

Fig.16. V-P Curve of the PV system Deployed Irradiation difference

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